Acousto-Optic Measurements in CFRP Laminates Using Fiber Bragg Grating Sensors

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ABSTRACT

In light of ongoing efforts to reduce weight but maintain durability, designers have examined the use of carbon composite materials for a number of aerospace and civil structures. Along with this research has been the study of determining reliable sensing and monitoring capabilities to avoid catastrophic failure. Fiber Bragg Grating (FBG) sensors are known to carry several advantages in this area one of which is their proven ability to detect acoustic emission (AE) lamb waves in composite structures. AE is produced in these materials by failure mechanisms such as resin cracking, fiber debonding, fiber pullout and fiber breakage. With such activity there is a noticeable change in Felicity Ratio (FR) in relation to the increase of accumulated damage. FR is obtained directly from the ratio of the stress level at the onset of significant emission and the maximum prior stress at the same AE level. The main objective of this paper is to describe the results of an acousto-optic experiment using FBG sensors and present FR as a potential way of determining accumulated damage in a carbon composite structure.

BACKGROUND

Carbon fiber-reinforced polymer (CFRP) composite materials are without a doubt playing a huge part in the advancement of engineering structures. With markets ranging from the aerospace industry, sporting goods and civil structures, composites offer a slew of attractive advantages over traditional materials. They have characteristics such as being light weight, high durability, corrosion resistance, high fatigue strength, and great design flexibility that are generating many areas of research and development within the science and engineering community [1].

The US-government agency, National Aeronautical Space Administration (NASA) has, for a number of years, used composite materials for a variety of

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functions on the recently retired space shuttle including its nose cone and other external parts. The possibility of using composites to build entire spacecraft in the future has been examined by NASA as they have, in Jan 2010, tested the first fully manufactured Composites Crew Module made of Carbon fiber materials.

In Civil engineering the corrosion resistance, along with lightweight (approximately one-fifth the weight of steel) with comparable strength, and ease of installation have made composite materials attractive alternatives to traditional materials to reduce dead load and extend structure life [2]. Particularly in the construction of bridges, composites are being used to rehabilitate deteriorating concrete components by externally bonding a CFRP laminate to immediately improve the strength of parts and keep them intact. Some designers have been looking at using CFRP instead of steel as rebar for several years, however in many cases entire bridge decks have now been built and installed made totally of composite materials. (e.g., the No-Name Creek Bridge in Russell, Kansas, and the Muddy Run Bridge on Delaware State Route 896)

As CFRP and other composite materials begin to gain ground in industry there are areas that must be further developed in order to increase their overall acceptance. The formation of composites involves the bonding of two or more constituents therefore a high quality interface must be achieved to ensure optimum transfer of forces in the material. Anomalies present at this level can be classified as microscopic defects which include cracked fibers, variations in fiber diameter, non-uniform or lack of fiber-matrix bonding. Because of its usual small reduction in strength, these levels are suggested to be regarded as a composite material property [3]. It is to defects on the macroscopic level however, that greater care should be given to identifying and either reducing or eliminating their effect on the overall performance. These defects, which are produced either during manufacture, transport and construction or in-service damage, are mostly related to misalignment of fibers, voids in the matrix, wrinkling of fabric and delamination of plys. Among researchers, attention has already been dedicated to these types of damage and their effect on structural integrity [4].

The inevitability of damage, especially in-service, of composites has prompted major interest in non-destructive evaluation technology (NDT or NDE) and structural health monitoring (SHM) of composites materials as a collection of tools and testing techniques that can be used to detect defects and measure physical or mechanic characteristics of a material. Several traditional methods have been established to test concrete, wood and other metallic materials including various types of visual inspection; however in this case the majority of defects occur inside the composite material, often in such an insidious way that it demands more sophisticated testing and procedures. SHM seeks to permanently install compatible types of sensors that can function as sort of a nervous system for structures.

FIBER BRAGG GRATING AND THE ACOUSTO-OPTIC CONCEPT

Fiber optical sensors have shown themselves to be one of the most promising SHM techniques which are mature enough for use in “smart materials”. This is particularly evident in the aerospace industry where you can find them on a number of aircraft in order to conduct strain measurements. Their small-diameter

has a very small footprint on the entire structure and the presence of such provides a far greater mass reduction than other currently applied sensory methods. Several Fiber optics sensors can be written in a single strand allowing multiplexing and improved sensor density. Additionally, Fiber-optic Bragg Gratings are immune to electromagnetic radiation [5].

A Bragg grating is a permanent, periodic perturbation of the refractive index which is laterally exposed in the core of an optical fiber, extending over a limited length of the fiber. The grating is characterized by its period, amplitude and length, usually 1–20 mm. Such a periodic structure acts as a filter for light traveling along the fiber line. It has the property of reflecting light in a predetermined range of wavelength centered on a peak wavelength value. This value, the Bragg wavelength λ_B, is given as follows:

$$\lambda_B = 2\check{n}_{eff}\Lambda \tag{1}$$

where Λ is the grating period and $\check{n}_{eff}$ is the mean effective refractive index in the grating region. External forces such as strain, pressure or a temperature change lead to changes in the grating period and in the effective refractive index. Consequently, the wavelength of the light reflected from the grating varies. The relative shift of the Bragg wavelength for an applied strain along the fiber axes ε_z and a temperature change ΔT is, in a first approximation, given as follows:

$$\Delta\lambda_B / \lambda_B = C_\varepsilon\varepsilon_z + CT\_T \tag{2}$$

where C_ε and C_T are material constants usually determined from calibration experiments. Typical values for the relative shift of the Bragg wavelength are ~10 pm K^{-1} for the temperature sensitivity and ~1.2 pm/μstrain for the strain sensitivity in the 1.5 μm wavelength region. When coupled with a high resolution interrogation system, the FBG's ability to detect such micro strain with such high absolute accuracy opens it up to various sensing applications such as Acoustic Emission events (AE) [6].

Fiber Bragg Grating (FBG) optical sensors have had heavy use in structural heath monitoring applications because of their low intrusiveness and ease of integration that is unparalleled by many other sensors.

Work done by Betz, et al. [5] has demonstrated the capability of FBGs for detecting acoustic lamb waves by using the interrogation method. By probing the grating spectrum with a narrow wavelength laser, any shifts in the spectrum will modulate the reflected power. In Figure 1 an FBG reflection spectrum is shown. The optical power reflected depends on the wavelength of the narrow tunable laser. The linear portion of the spectrum is found on either edge of the spectra where the power is linear from about 20 to 80 percent of the maximum of the spectrum.

In the measurement the laser is tuned to a fixed wavelength. Typically, at the full width half-maximum since this maximizes the range of measurement in both directions. Traveling acoustic waves in the material are a series of compression and expansion waves yielding time dependant strain, *$\varepsilon(t)$.* This strain in the FBG is measured and recorded as the acoustic emission event. The equation for the varying strain is given by:

$$\varepsilon(t) = [\Delta U(t)\, R_0/U_0](dR/d\varepsilon) \quad (3)$$

Where $\Delta U(t)$ is the electric voltage from the detector, R_0 is the initial reflection, U_0 is the voltage at time $t = 0$, and $dR/d\varepsilon$ is determined from the material properties.

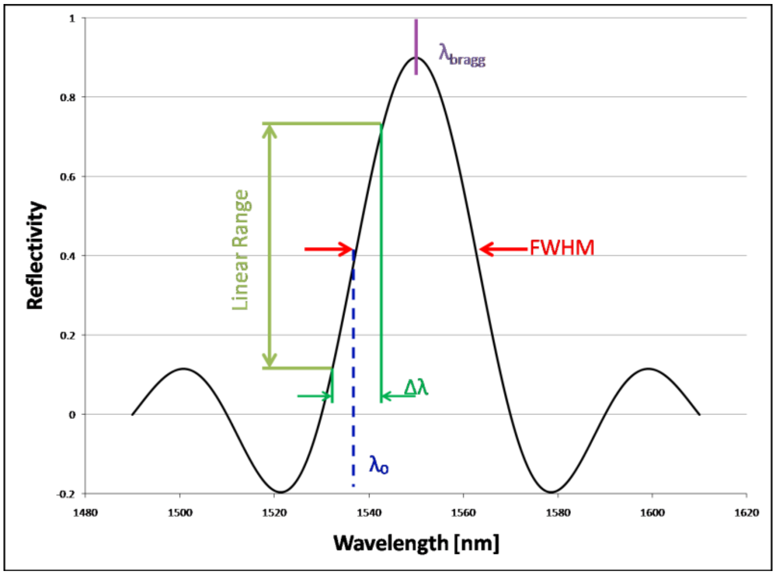

Figure 1. Typically reflected spectrum of a Fiber Bragg Grating showing the linear region and FWHM where our light source would be tuned.

EXPERIMENTAL WORK

Experiments were conducted where 9 CFRP laminates of two different lay-up designs were tensile tested for damage-induced acoustic emissions. A *Tunics Plus* Tunable Laser that is able to send a wavelength of light to the precision .001 nanometer was used to interrogate the FBG sensors. Light from the tunable laser is passed through a fiber splitter which has one end that is directly connected to a single FBG optic fiber that is attached to our CFRP specimen. The other end is connected to another fiber splitter that has one end coupled to another FBG sensor on our specimen. The light reflected by our gratings is sent back through the fiber splitter into two different detectors which convert the light into an electronic signal. Our first FBG sensor is connected to a *New Focus* Front-End Optical Receiver with an adjustable high- and low-pass filter as well as electronic gain control which is sent directly to the 8 channel DWC (Digital Wave Corp., Centennial, CO) FM-1 sensor box of the AE computer system via Bayonet Neill-Cables (BNC). The other sensor is sent first to a *New Focus* broadband Front-End Optical Receiver then to a preamplifier which is then connected to the FM-1box that is fed into the AE system. Each of the traditional AE sensors were all fed through preamplifiers before being connected to the computer. The AE data acquistion system uses *Digital Wave Explorer* analysis software to record and perform preliminary filtering to test data. Our samples were loaded in a *MTS 810* load testing machine equipped with *MultiPurpose Testware* for controlling loading procedure. The setup as stated above is illustrated below in Figure 2.

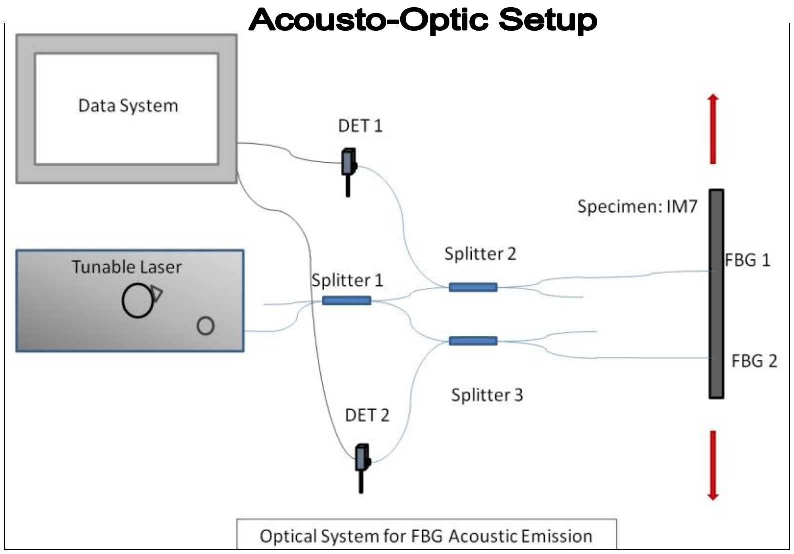

Figure 2. Diagram showing the Acousto-optic setup used in the experiment.

Only one light source was used for two different FBGs so both needed to be selected with identical wavelengths for simultaneous sensing. Strain caused by the curing of the fiber bonding agents, temperature, and manufacturing errors often caused uneven strain fields in both of our sensors therefore the laser was mostly tuned to optimize one of the sensors making it more sensitive to the flexural waves. Additionally, light seepage at each fiber coupler and instability in the laser produced an abundance of noise in our signal obtained from the FBG that wasn't found in the PZT signal.

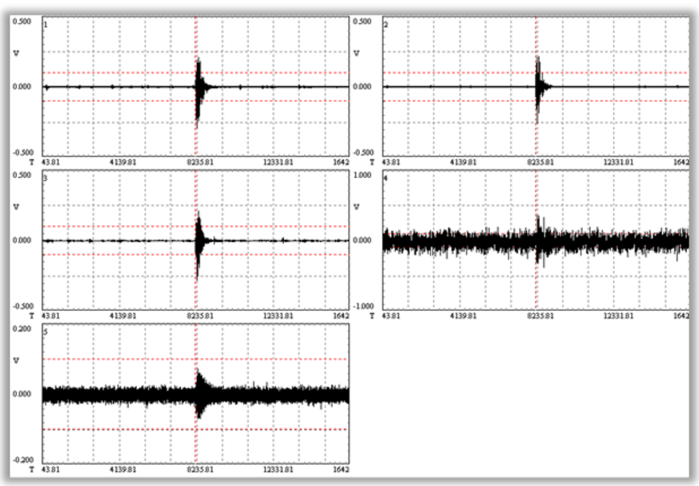

Figure 3. Showing the relative visibility of the 30 pt smoothed signals of both the traditional AE sensors (top 3) and the FBG sensors (bottom 2).

Because of the low signal-to-noise ratio of the FBG there was a need for the decrease of captured noise and an increase in visibility of each event. Therefore in order to distinguish the FBG detected signal the AE wave spectrums were averaged (smoothed) every 30 data points which rendered a much cleaner signal comparable to that of the PZT [Figure 3].

Felicity Ratio

Most of the loading procedures performed were such that they were intended to show accumulated damage deduced from a violation of the Kaiser Effect. The Kaiser Effect states that after a material has experienced a loading, unloading, and reloading, there should be no new significant AE events in the reloading of the material until the previous highest load is either matched or exceeded. Typical materials that deform elastically exhibit this behavior. However, in a composite, violation of the Kaiser Effect is indicative of permanent damage in the specimen due to irreversible flow or viscous loss. This violation is known as the Felicity Effect which is the presence of significant AE prior to the previous maximum load on the structure. This degree can be numerically described by the *Felicity Ratio* (FR) which is calculated by the following equation:

$$FR = \frac{\text{Load at which significant AE occurs during loading}}{\text{Load at which significant AE occured during prior loading}} \tag{4}$$

If the FR calculated is greater than or equal to 1 then the Kaiser Effect has not been violated. Once the FR is at a value less than 1 the Felicity Effect has occurred. When examined throughout the life of a composite structure, a decrease in the FR proposes to be indicative of the accumulated damage in the material. Such work has been done using traditional AE sensors on carbon/epoxy tows [8].

TABLE 1. SUMMARY TESTS RESULTS

Fiber/Resin	**Lay up**	[1]**Test**	**Max Tensile** (lbf)	**Max Strain** (in/in)	**FR seen**	[2]**Failure**
AS4/8552	8 ply _(+- 45)	SSM	3129	N/A	N/A	XGM
AS4/8552	8 ply _(+- 45)	SSM	2432	N/A	**Yes**	XGM
AS4/8552	8 ply _(+- 45)	SSM	3002	0.083	**Yes**	XGM
AS4/8552	8 ply _(+- 45)	SSM	2974	0.085	**Yes**	XGM
AS4/8552	8 ply _(+- 45)	SSM	3225	0.091	**Yes**	XGM
Mean			2952	0.086		
Std Dev			308	0.004		
IM7/8552	16 ply _ $(0/90)_{8s}$	SSM	11986	0.011	**Yes**	LAT
IM7/8552	16 ply _ $(0/90)_{8s}$	SSM	14043	0.012	**Yes**	LAT
IM7/8552	16 ply _ $(0/90)_{8s}$	SSM	14783	0.013	**Yes**	LAT
IM7/8552	16 ply _ $(0/90)_{8s}$	CLU	14487	0.012	**Yes**	LAT
Mean			13825	0.012		
Std Dev			1263	0.001		

[1.] SSM-Step Stress Method, CLU – Complete Load-Unload. [2.] Failure abbreviations per *Ref.* [7]

Intermittent Load-Hold schedules per ASTM 2661 were performed where each sample underwent a ramp to a certain percentage of its ultimate tensile strength, held for 2 minutes and then unloaded to relieve stress. It is then reloaded to a slightly higher load and held again. It then repeats the previous sequence until failure. Figures 4 and 5 shows the AE events recorded by the PZT and AE sensors as well as the FR trend found from the tests.

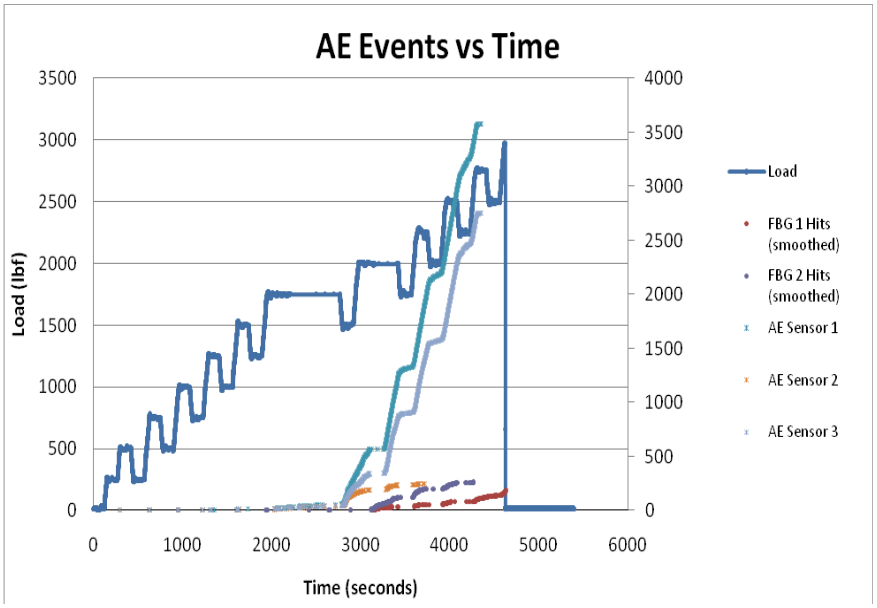

Figure 4. The number of acoustic hits recorded by each sensor throughout the duration of the test.

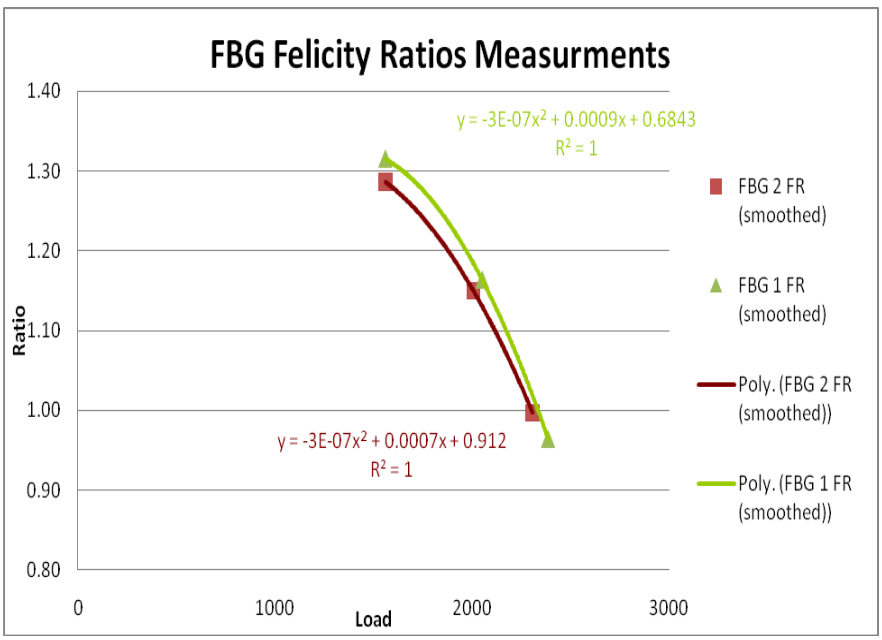

Figure 5. Showing a decreasing trend of Felicity Ratio due to progressive damage in CFRP laminate.

Determining the onset of significant acoustic emission is important when calculating the Felicity Ratio. The method employed in this case was that of taking the first 10 hits and then averaging the corresponding loads to get our onset value. This has shown to be an effective way of obtaining such measurements in composite tows using traditional piezoelectric AE sensors [8]. Above in Figure 5 we see the trend of Felicity Ratios obtained from our test using the FBG sensors. Since the trend has a negative slope we can tell that the FBG notices the onset of new AE hits earlier with each successive loading period. This is directly indicative of damage accumulating inside the material.

CONCLUSION

From this work it can be concluded that the FBG has the ability to detect acoustic events as well as record Felicity Ratio measurements in laminate CFRP structures. However, an AE system is needed that optimizes this technique by eliminating optical noise in addition to providing filtering methods suitable for acousto-optic interrogation. Fiber optic sensors allow for integration with composite materials without the extra mass and interference caused by traditional acoustic emission sensors. A greater number of standard Felicity Ratio tests of a given composite laminate can render a decreasing trend indicative of its accumulated damage. A firmly established trend combined with the acousto-optic detection of the FBG offers a promising method of structural health monitoring.

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